CO2, N2O, and CH4 Fluxes from Soil in Siberian-Taiga Larch Forests with Different Histories of Forest Fire

Tôhoku Geophys. Journ. (Sci. Rep. Tôhoku Univ., Ser. 5), Vol. 36, No. 2, pp. 77-89, 2001

CO_2, N_2O, CH_4 Fluxes from Soil in Siberian-Taiga Larch Forests with Different Histories of Forest Fire

TAKUJI SAWAMOTO*, RYUSUKE HATANO*, MASATO SHIBUYA*,
KUNIHIDE TAKAHASHI*, A.P. ISAEV** and R.M. DESYATKIN**

*Graduate School of Agriculture, Hokkaido University, Sapporo, 060-8589
**Institute of Biological Problems of Cryolithozne, Russian Academy of Sciences

(Received October 20, 2000; accepted December 27, 2000)

Abstract: Many researchers have pointed out that the ratio of tree root respiration to soil respiration is high in forest ecosystems, ranging from 40% to 80% (e.g. Edwards *et al.*, 1989). We hypothesized that a decline or loss of trees by forest fire or cutting would decrease soil respiration, and forest regeneration would increase tree root respiration and soil respiration. To confirm this hypothesis, we measured soil respiration at sites with different histories of forest fire in Yakutsk, east Siberia, in 1997 and 1998. The mean soil respiration (10^{-6} g CO_2 m^{-2} s^{-1}) in an intact larch forest was significantly higher (161) than at a treeless site burnt in 1992 (61). At a regenerating larch forest site burnt in 1973, the mean soil respiration was almost the same (151) as in the intact forest. The ratio of tree root respiration to soil respiration was estimated to be >70% by determination of microbial respiration of the soils. These results support the hypothesis.

Few studies of fluxes of N_2O and CH_4 have been done in Siberia Taiga forest. We estimated fluxes of N_2O and CH_4 from gas concentration and gas diffusion coefficients in the soil profile. Soil took up CH_4 from the atmosphere regardless of forest fire history, but neither emission nor uptake of N_2O was detectable. The range of CH_4 flux was from -5 to -15 (10^{-9} g CH_4 m^{-2} s^{-1}), which is in the range measured in boreal forests of northern Europe.

Key words: forest fire, methane uptake by forest soil, root respiration, Siberian Taiga, soil respiration

1. Introduction

Carbon cycling in forest-soil ecosystems comprises photosynthesis and respiration by plants, litter-fall, and soil respiration. Soil respiration is defined as the release of CO_2 from soil to the atmosphere, and comprises soil microbial respiration, soil faunal respiration, and plant root respiration. Therefore, soil respiration reflects the productivity or degree of eutrophy of the ecosystem (Raich and Schlesinger 1992; Singer and Munns 1999). Many researchers have pointed out that the ratio of tree root respiration to soil respiration is high (e.g. 50% [Nakane, 1983]; 43%-78% [Edwards *et al.*, 1989]; 40% [Holt *et al.*, 1990]) in forest ecosystems. Eguchi *et al.* (1997) estimated that 69% of soil respiration in a deciduous forest in Hokkaido, Japan, was absorbed by trees, based on the CO_2 concentration gradient in the canopy, and that 70% of soil respiration was derived from tree root respiration. Estimates by Eguchi *et al.* (1997) suggest that almost all tree root respiration will be reabsorbed by trees.

Forest, particularly boreal forest in Russia, plays an important role in the carbon storage in terrestrial ecosystems (Kolchugina and Vinson, 1993; IIASA, 1997; Kasischke, 2000). However, forest fire changes the forest from a sink to a source of atmospheric CO_2, one of the greenhouse gases (Auclair and Carter, 1993; Kurz and Apps, 1995). In east Siberia, low precipitation in spring allows frequent forest fires (Valendik, 1996), which release CO_2 into the atmosphere (Dixon and Krankina, 1993) and have a great influence on forest regeneration (Matveev and Usoltzev, 1996) and carbon cycling in the Taiga ecosystem. After a forest fire, carbon cycling in the forest-soil ecosystem changes drastically; this change is affected by the severity of the fire. The physical (Rouse, 1976), chemical (Lucarotti, 1980; Moore, 1980; Pietikäinen and Fritze, 1995), and biological (Bääth, 1980; Lucarotti, 1980; Pietikäinen and Fritze, 1995) properties of the soil are affected, leading to a change in soil respiration. In addition, a decline in tree root respiration due to tree damage or death after fire would decrease soil respiration, and loss of the canopy might influence trees' absorption of CO_2 from soil respiration.

We investigated soil respiration in larch forests with different histories of forest fire in Yakutsk in eastern Siberia (Sawamoto *et al.* 2000). At severely burned sites with no trees, soil respiration was significantly lower than in intact forests. This suggests that the decrease in soil respiration was probably due to the loss of tree root respiration. If this is true, then soil respiration in a regenerating forest might be in the same range as that in an intact forest and significantly higher than that at a treeless site. Our first objective, then, was to confirm this hypothesis.

In contrast to waterlogged soils, aerated and dry soils generally act as sinks for atmospheric CH_4 (Schütz *et al.* 1990). Natural undisturbed soils of tropical and temperate forests emit N_2O to the atmosphere (Bouwman 1990). However, few studies of fluxes of N_2O and CH_4 have been done in boreal (taiga) forest. Our second objective was to determine fluxes of N_2O and CH_4 in taiga forests in Yakutsk with different histories of fire.

2. Materials and methods

2.1. Site description

In the first ten days of August 1997 and 1998, we measured plants, conducted soil surveys, and measured soil respiration and fluxes of N_2O and CH_4 in four ecosystems —intact larch (*Larix cajanderi*) forest (Cont), forest burned weakly in 1996 (W96), forest burned severely in 1992 (S92), and regenerating larch forest burned severely in 1973 (S73) —in Yakutsk.

In Yakutsk city (62°05′N 129°45′E) the annual mean temperature is −10.0 (°C) and mean temperature values for January (the coldest month) and July (the hottest month) are −41 and +18.7 (°C), respectively. The annual mean precipitation is 237 mm (National Astronomical Observatory 1998). All the sites were located at a distance of about 40 km (62°13′N 129°10′E) north-west of Yakutsk city and were on a flat plateau where the elevation was about 220 m. The soils were sandy Spodosols (Soil Survey Staff

1990).

The forest floor of Cont was covered with litter a few centimeters deep, and the small vegetation was dominated by *Vaccinium vitis-idaea*. Stem density was 2,235 trees ha^{-1}. Mean tree height was 8.97 m, and above ground biomass weighed 124 Mg ha^{-1}. Details of plant investigations at Cont are given by Yajima *et al.* (1998). F and E horizons were present, and a permafrost layer was present below a depth of about 110 cm. Soil horizons (cm) were L (−8−−5), F/H (−5-0), E (0-4), B_2 (4-24), B_3 (24-57), C (57-100), and C_f (100+).

W96 was contiguous with Cont, but the permafrost had melted, and ground water was present. Larch trees were still standing but litter and vegetation on the forest floor had disappeared owing to the burning. But the F/H horizon was recognizable. Soil horizons (cm) were F/H (−2-0), E (0-10), B_{21} (10-18), B_{22} (18-38), B_3 (38-48), and C (48-123+).

S92 was also contiguous with Cont. Almost all the trees had fallen and the litter and vegetation on the original forest floor had burned completely. Other vegetation, including bryophyte (*Marchantia polymorpha*) and herbs (*Chamaenerion angustifolium* (*Epilobium angustifolium*)), had invaded. Details of plant investigations at S92 are given by Yajima *et al.* (1998). The F/H and E horizons were not recognizable. The permafrost had melted, and ground water was present. Soil horizons (cm) were A_1 (0-4), A_{12} (4-14), AB (14-28), B_2 (28-31), B_3 (31-57), and C (57-180+).

The larch trees in S73 were all less than 22 years old. The forest floor was covered with litter a few centimeters deep, and the small vegetation was dominated by *Aulacomnium palustre* and *Calamagrostis lapponica*. Stem density was 10,000 trees ha^{-1}. Mean tree height was 4.68 m, and above ground biomass weighed 16.2 Mg ha^{-1}. Details of plant investigations in S73 are given by Shibuya *et al.* (1999). F and E horizons were present, and a permafrost layer was present below a depth of about 100 cm. Soil horizons (cm) were L (−2-0), A (F/H) (0-4), AB (4-11), E (11-23), B_{2h} (23-38), B_{2ir} (38-48), B_{2irg} (48-88), B_3 (88-98), and B_{3f} (98+).

2.2. *Soil survey and soil analysis*

At each survey site, the soil profile was investigated as far as the permafrost layer or water table. Distribution of temperature, water saturation ratio, organic carbon content, and bulk density were measured (Sawamoto *et al.*, 2000). Undisturbed soil samples were taken from some horizons, and the relative gas diffusion coefficient (D/D_0) was measured by the method of Osozawa and Kubota (1987). The distribution of D/D_0 in profile was predicted from the relationship between air-filled porosity and D/D_0.

2.3. *Measurement of soil respiration in situ and soil microbial respiration*

A closed chamber was used to measure the soil respiration *in situ* (Sawamoto *et al.*, 2000). Measurements were conducted in early morning and afternoon to cover the low soil temperature. To measure soil microbial respiration per gram of soil for each horizon, air-dried soil samples were incubated by the method of Sawamoto *et al.* (2000).

The temperature and water saturation ratio were set to the same as those in the soil profile in situ. We assumed that CO_2 from soil microbial respiration of all horizons diffused to the atmosphere and contributed to soil respiration *in situ*. However, permafrost layer was recognized near the depth of 1 m at Cont and S73. Therefore, to compare the soil microbial respiration *in situ*, we calculated soil microbial respiration per unit area within 1 m depth. The soil microbial respiration per unit area within 1 m depth (g CO_2 m^{-2} s^{-1}) was calculated by multiplying the soil microbial respiration per gram of soil (g CO_2 g^{-2} s^{-1}), horizon thickness (m), and bulk density (g m^{-3}), and integrating them within 1 m depth.

2.4. Fluxes of N_2O and CH_4

N_2O and CH_4 concentrations were determined at some depths to 30 cm. A metal pipe (9.7 mm o.d., 8.0 mm i.d.) was installed to a chosen depth, and a gas sampling port was attached. One or two days after installation, 15 mL of air inside the pipe was drawn out and injected into a 10-mL vacuum tube. Standard gases with known concentrations of N_2O and CH_4 had been injected into a vacuum tube by the same method before the field trip and taken from Sapporo to Yakutsk and back to Sapporo. After arrival in Japan, N_2O and CH_4 were analyzed by a gas chromatography equipped with ECD or FID detectors. Concentrations were calculated by calibration against the standard gases. N_2O and CH_4 fluxes were calculated by a diffusion equation described by Fick's law (Rolston, 1986). The detection limits of these fluxes were 0.75 (ng N_2O-N m^{-2} s^{-1}) and 1.69 (ng CH_4-C m^{-2} s^{-1}).

3. Results

3.1. Soil physico-chemical properties

Figure 1 shows soil temperature profiles. At all sites, soil temperature decreased with increasing depth. Higher soil temperatures were observed at S92 and W96 than at Cont. However, soil temperature profiles at S73 and Cont were similar. Figure 2 presents water saturation ratio profiles. Water saturation ratio increased with depth. Treeless site (S92) had higher water saturation ratios than the other sites. Figure 3 shows the distributions of organic carbon content in the soil profiles. The organic horizons had high organic carbon contents (>20%). The A-horizon at S92 and S73 had higher organic carbon content than that at Cont.

3.2. Soil respiration in situ

Figure 4 shows the relationships between soil respiration and soil temperature at 3 cm depth. The soil respiration rate ranged widely from 23 to 310 (10^{-6} g CO_2 m^{-2} s^{-1}). The mean soil respiration rate of S92 (61) was significantly lower than that of Cont (161). W96 had an intermediate soil respiration rate (81). S73 had almost the same mean soil respiration rate (151) as Cont. In Cont, W96, and S92, there was a significant (5% level) relationship between soil respiration and soil temperature at 3 cm depth. The mean soil

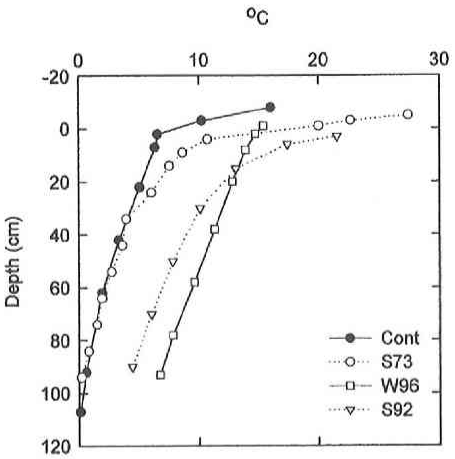

Fig. 1. Distribution of soil temperature in soil profile at intact larch forest (●), a larch forest burnt weakly in 1996 (□), treeless site burned severely in 1992 (▽), and regenerating larch forest burned severely 1973 (○).

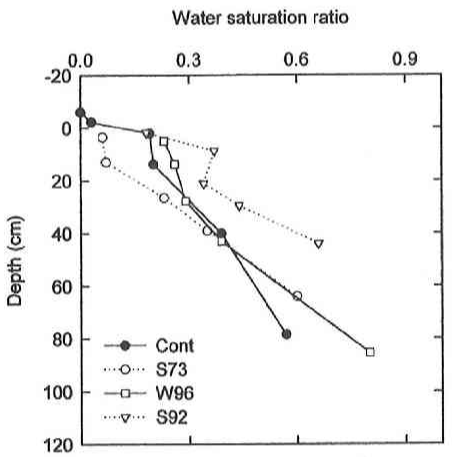

Fig. 2. Distribution of water saturation ratio in soil profiles at intact larch forest (●), a larch forest burnt weakly in 1996 (□), treeless site burned severely in 1992 (▽), and regenerating larch forest burned severely 1973 (○).

respiration rates in Cont and S73 were similar to the results of Anderson (1973) and Gordon *et al.* (1987).

3.3. Microbial respiration

Soil microbial respiration per gram of soil (ng CO_2 g^{-1} s^{-1}) of L- and F-horizons ranged from 0.25 to 2.31. That of F-horizons at Cont and W96 were 1.89 and 2.31, respectively, which was higher than those of the mineral horizons, ranged nil to 0.95. In L- and F-horizons, there was no relationship between soil microbial respiration and

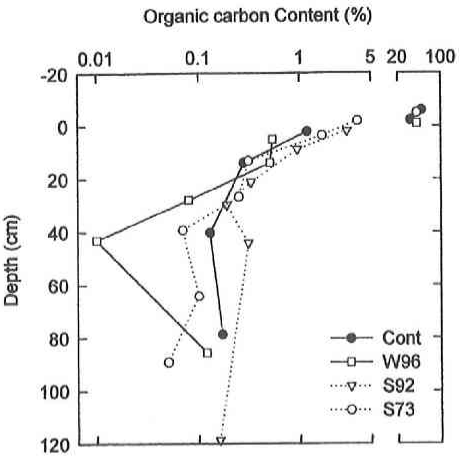

Fig. 3. Distribution of organic carbon content in soil profiles at intact larch forest (●), a larch forest burnt weakly in 1996 (□), treeless site burned severely in 1992 (▽), and regenerating larch forest burned severely 1973 (○).

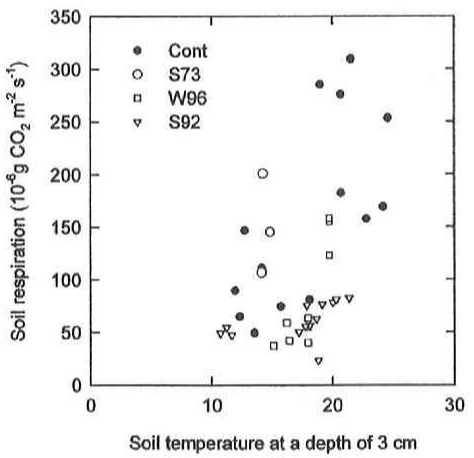

Fig. 4. Relationship between soil temperature at a depth of 3 cm and soil respiration at intact larch forest (●), a larch forest burnt weakly in 1996 (□), treeless site burned severely in 1992 (▽), and regenerating larch forest burned severely 1973 (○).

incubation temperature, organic carbon content, and water saturation ratio. However, in mineral horizons, soil microbial respiration per gram of soil showed significant positive relationships with incubation temperature (Fig. 5) and organic carbon content (Fig. 6). And A-horizons had considerably higher soil microbial respiration than the other mineral horizons (Figs. 5 and 6).

3.4. Fluxes of N_2O and CH_4

Figure 7 shows the distribution of concentrations of N_2O and CH_4 in the soil profiles.

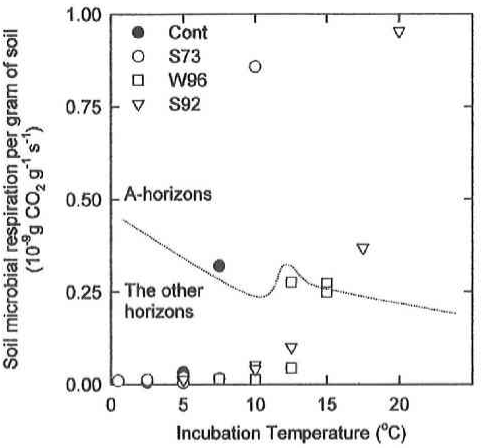

Fig. 5. Relationship between incubation temperature and soil microbial respiration per gram of soil in mineral horizons at intact larch forest (●), a larch forest burnt weakly in 1996 (□), treeless site burned severely in 1992 (▽), and regenerating larch forest burned severely 1973 (○).

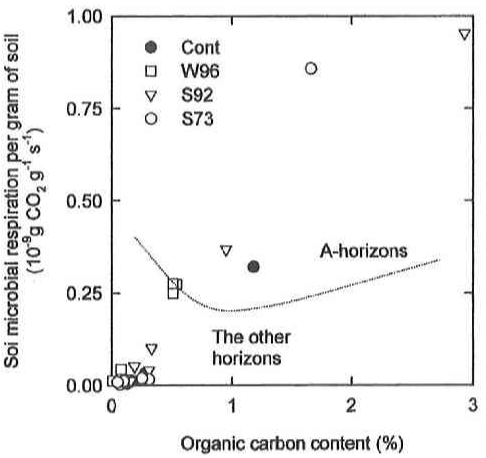

Fig. 6. Relationship between organic carbon content and soil microbial respiration per gram of soil in mineral horizons at intact larch forest (●), a larch forest burnt weakly in 1996 (□), treeless site burned severely in 1992 (▽), and regenerating larch forest burned severely 1973 (○).

N_2O concentration gradient was not significant at any sites, which indicates that neither emission nor uptake was detectable. Methane concentrations were lower in the soil profile than in the atmosphere, which indicates uptake of methane by soil at all sites.

Figure 8 shows distributions of measured and predicted D/D_0 in the soil profiles. The predictions agreed closely with the measurements. D/D_0 decreased with increasing depth. Calculated CH_4 fluxes (10^{-9} g CH_4 m^{-2} s^{-1}) were -5.60 at Cont, -5.15 at S73, -15.4 at W96, and -6.32 at S92.

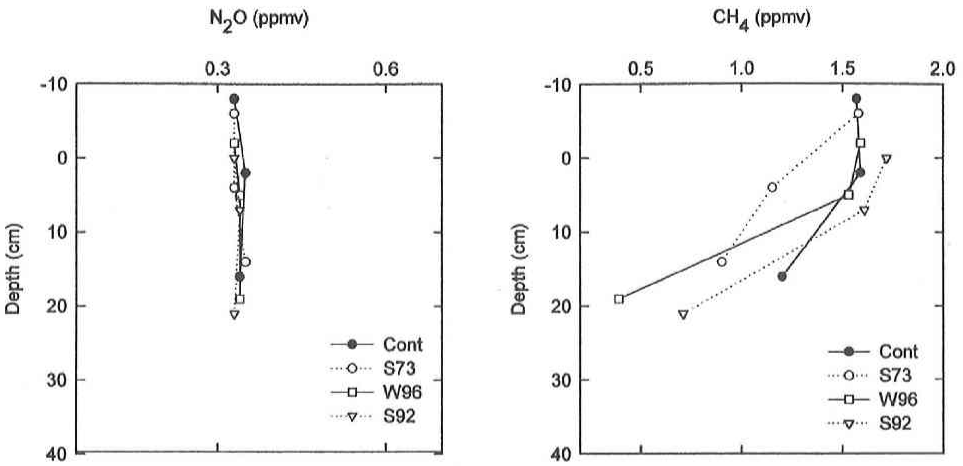

Fig. 7. Distribution of concentrations of N_2O and CH_4 in soil profiles at intact larch forest (●), a larch forest burnt weakly in 1996 (□), treeless site burned severely in 1992 (▽), and regenerating larch forest burned severely 1973 (○).

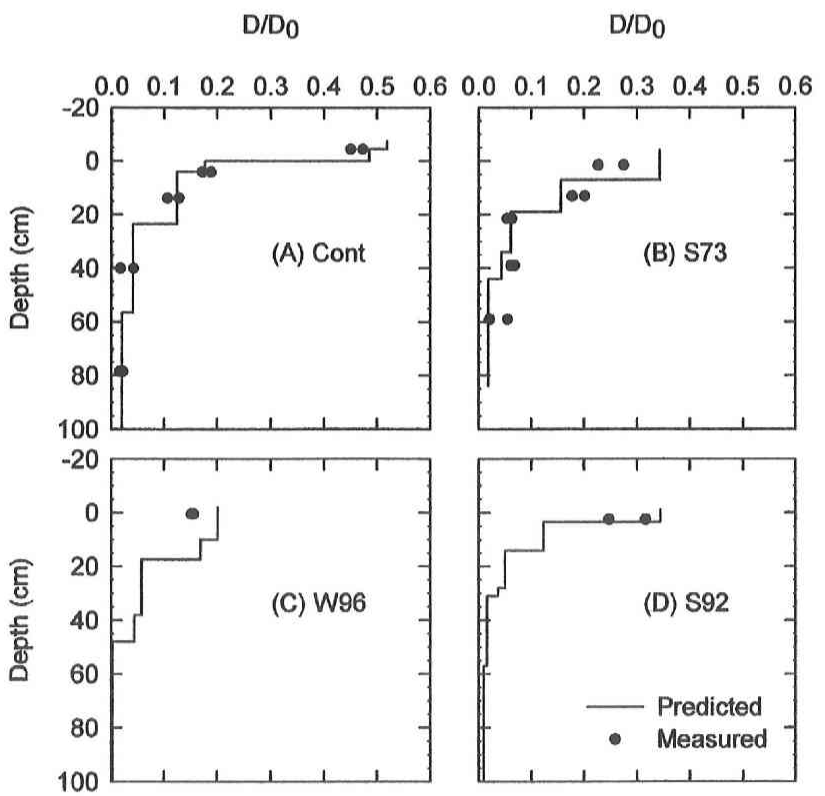

Fig. 8. Distribution of relative gas diffusion coefficient (D/D_0) in soil profiles. ● and solid line shows measured and predicted value, respectively.

4. Discussion

4.1. Soil physico-chemical properties

Forest fires influenced the physical properties of the soil. Soil temperature at burned sites (W96 and S92) was higher than that at Cont. However, soil temperature at regenerating forest (S73) was almost similar to Cont (Fig. 1). These facts indicate that heat produced by burning or direct sunlight brought about by collapse of the trees increased soil temperature. And, water saturation ratio at the treeless site (S92) was higher than that at the sites with trees (Cont, W96, and S73) (Fig. 2), suggesting that water uptake by tree roots decreased the soil moisture. Rose (1976) measured the increase in soil temperature and the decrease in net radiation after a forest fire, and obtained results similar to our results.

Soil chemical properties also had changed after forest fire. The organic carbon contents of A-horizons at severely burned sites (S92 and S73) were higher than that at Cont (Fig. 3). This is probably due to that the forest fire supplied organic matter or ashes to the A-horizons.

4.2. Soil microbial respiration and an estimation of tree root respiration

In general, soil microbial respiration increases with increased temperature (Kirscbaum, 1995), and the soil microbial biomass increases in proportion to the soil organic carbon content (Anderson and Domsch, 1980). In the mineral horizon, high temperature and high organic carbon content increased soil microbial respiration per gram of soil (Figs. 5 and 6). These findings agree with the results of Kirscbaum (1995) and Anderson and Domsch (1980).

Table 1 summarizes mean values of soil respiration, microbial respiration within 1

Table 1. Summary of soil respriration *in situ*, soil microbial respiration by laboratory incubation, and an estimate of soil microbial respiration *in situ* and the ratio of tree root respiration to soil respiration.

Site*1	Mean value of soil respiration *in situ**2	Soil microbial respiration within 1 m depth by laboratory incubation			An estimation of soil microbial respiration *in situ*	An estimation of the ratio of tree root respiration to soil respiration
		L and F horizons	Mineral horizons	All horizons		
	(A)	(B)	(C)	(D=B+C)	(E=(D/106)×61)	(F=(A−E)/A×100)
	10^{-6} g CO_2 $m^{-2}s^{-1}$					%
Cont	161 a	7	26	33	19	88
S73	151 ab	7	55	62	35	77
W96	81 bc	2	81	83	48	41
S92	61 c	–	106	106	61	0

*1 Cont, an intact larch forest; S73, a regrowing larch forest burnt in 1973; W96, a larch forest burnt weakly in 1996; S92, a treeless site burnt severely in 1992

*2 Significant at 5% level LSD.

m depth by laboratory incubation, and an estimation of microbial respiration *in situ* and ratio of tree root respiration to soil respiration. Organic horizons had lower microbial respiration than mineral horizons (Table 1 column B vs. C), which was due to the small values of bulk density in organic horizons. In the mineral horizons, S92 had higher soil microbial respiration than Cont and S73 (Table 1 column D). And S92 had higher organic carbon content in A-horizon and higher soil temperature than Cont (Figs. 1 and 3). Therefore, it is suggested that the increase in soil microbial respiration at S92 was due to high soil temperature and high organic carbon content in A-horizon.

Permafrost layer was recognized near the depth of 1 m in Cont and S73 (Fig. 1) and the laboratory incubation showed significantly higher soil microbial respiration in the A-horizons than the C horizons (Figs. 5 and 6). Therefore, the soil microbial respiration integrated within 1 m depth is considered to represent soil microbial respiration *in situ*. However, soil microbial respiration values per unit area within 1 m depth (g CO_2 m^{-2} s^{-1}) at S92 was higher than soil respiration *in situ* (Table 1 column A vs. D). One of this discrepancies is probably a flush of organic matter decomposition when the incubation was conducted.

For the modification of the discrepancy, we conducted following treatment. Since S92 had almost no trees, we considered that tree root respiration was nil and that soil microbial respiration within 1 m depth was almost equal to the soil respiration at S92. Therefore we calculated an estimation of soil microbial respiration *in situ* on the assumption that microbial respiration at each site occurred in the same ratio as the incubation measurement (Table 1 column E). Furthermore, on the assumption that the residual respiration was from tree root, the ratios of tree root respiration to soil respiration were calculated to be >70% in Cont and S73 (Table 1 column F).

4.3. Soil respiration in the regenerating forest

Soil respiration at the regenerating forest (S73) was almost the same as at Cont and significantly higher than at S92 (Fig. 4 and Table 1). This confirmed our hypothesis, that soil respiration in a regenerating forest would be in the same range as in an intact forest and significantly higher than in a treeless site. And the estimation of the ratio of tree root respiration to soil respiration (Table 1) shows that high percentage (>70%) of soil respiration was from tree root respiration at intact and regenerating sites. Therefore, it is concluded that regeneration of larch forest increased tree root respiration and consequently increased soil respiration.

The soil respiration *in situ* at W96 was between those at Cont and S92 (Fig. 4 and Table 1). The ratio of tree root respiration to soil respiration at W96 was lower than at Cont (Table 1). This may be due to fire damage to the trees.

4.4. Fluxes of N_2O and CH_4

Fig. 9 shows the ranges of N_2O emission from tropical and temperate un-cultivated soils, summarized by Bouwman (1990). Our N_2O emissions in Yakutsk were under the detection limit (Fig. 7), which was lower than the values in tropical and temperate forests

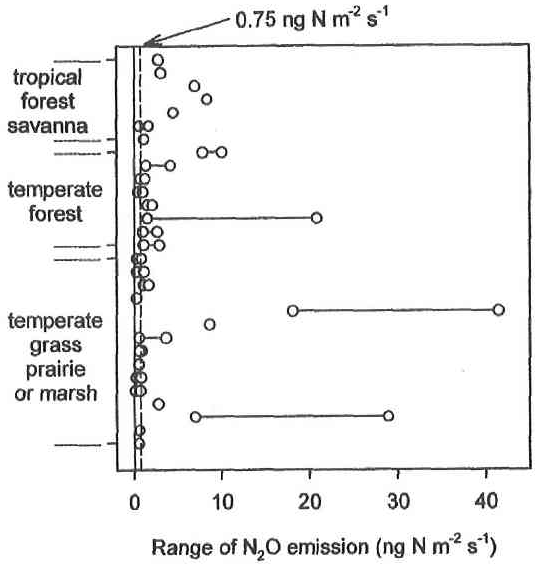

Fig. 9. N_2O emissions from tropical and temperate un-cultivated soils, summarized by Bouwman (1990). For example, tropical forest and savanna includes 7 cases. The line of 0.75 shows the detection limit in this study.

(Fig. 9). It may be one of the reasons that the nitrogen mineralization rate in boreal forest soil is generally lower than tropical and temperate forest soils (Nadelhoffer *et al.* 1992).

Soil took up CH_4 at all sites (Fig. 7). This is probably because well-aerated top soil at all sites (Fig. 2) gave methanotrophic microorganisms good conditions for decomposition of CH_4 (Schütz *et al.*, 1990 ; Steudler *et al.*, 1996). These CH_4 fluxes are within the range of measurements from boreal forests in Scotland, Denmark, and Poland (-4.86 to -27.7 ; Dobbie *et al.*, 1996). According to the summary of Zelenev (1996), in Russian boreal forest there was no available data of CH_4 flux from dry soils in permafrost area, but the CH_4 flux was from -35.3 to -25.0 from dry soils in non-permafrost area. These results suggest that well-aerated forest soil in Siberia is a sink of atmospheric CH_4, regardless of history of forest fires.

5. Conclusions

Soil respiration at regenerating forest was similar to that at intact forest, and was greater than that at a treeless site. Tree root respiration was more than 70% of soil respiration at intact and regenerating forests, which indicates that regeneration of forest increases tree root respiration and consequently soil respiration. Regardless of history of forest fires, soil took up atmospheric CH_4, but neither emission nor uptake of N_2O was detectable.

Acknowledgements: We wish to express our appreciation to Dr. T. Ishiwata and Dr. M. Yokohama (Civil Engineering Research Institute, Hokkaido Development Bureau) for measuring total carbon and nitrogen in the soil samples, and to Dr. T. Nitta (Hokkaido National Agricultural Experiment Station) for measuring N_2O concentration. Ms. K. Kamide (Faculty of Agriculture, Hokkaido University) assisted with laboratory measurements. This study was supported by Japanese Grant-in Aids for Science Research from the Ministry of Education (09041140).

References

Anderson, J.M., 1973: Carbon dioxide evolution from two temperate, deciduous woodland soils, *J. Appl. Ecol.*, **10**, 361-378.

Anderson, J.P.E. and K.H. Domsch, 1980: Quantities of plant nutrients in the microbial biomass of selected soils, *Soil Science*, **130**, 211-216.

Auclair, A.N.D. and T.B. Carter, 1993: Forest wildfires as a recent source of CO_2 at northern latitudes, *Can. J. For. Res.*, **23**, 1528-1536.

Bouwman, A.F., 1990: Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere, *In* Soils and the greenhouse effect, Ed. A.F. Bouwman, p. 61-127. John Wiley & Sons Ltd., Great Britain.

Bääth, E., 1980: Soil fungal biomass after clear-cutting of a pine forest in central Sweden, *Soil Biol. Biochem.*, **12**, 495-500.

Dixon, K.D. and O.N. Krankina, 1993: Forest fire in Russia: carbon dioxide emissions to the atmosphere, *Can. J. For. Res.*, **23**, 700-705.

Dobbie, K.E., K.A. Smith, A. Prime, S. Christensen, A. Degorska and P. Orlanski, 1996: Effect of land use on the rate of methane uptake by soils in northern Europe, *Atmospheric Environment*, **30**, 1005-1011.

Edwards, N.T., D.W. Johnson, S.B. Mclaughlin and W.F. Harris, 1989: Carbon dynamics and productivity, *In* Analysis of biogeochemical cycling in Walker Branch Watershed, Ed. D.W. Johnson and R.I. Van Hook, p. 197-232, Springer-Verlag, Inc., New York.

Eguchi, S., T. Sakata, R. Hatano and T. Sakuma, 1997: Daily changes of CO_2 efflux from soil of deciduous broad-leaved forest and its significance as a CO_2 source for vegetation, *Jpn. J. Soil Sci. and Plant Nutr.*, 68, 138-147, (in Japanese with English abstract).

Gordon, A.M., R.E. Schlentner and K. Van Cleve, 1987: Seasonal patterns of soil respiration and CO_2 evolution following harvesting in the white spruce forests of interior Alaska, *Can. J. For. Res.*, **17**, 304-310.

Holt, J.A., M.J. Hodgen and D. Lamb, 1990: Soil respiration in seasonally dry tropics near Townsville, North Queensland, *Aust. J. Soil Res.*, 28, 737-745.

IIASA (International Institute for Applied Systems Analysis) 1997: Dialogue on Sustainable Development of the Russian Forest Sector—Volume 1: 22-44, Ed. S. Nilsson, Laxenburg, Austria.

Kasischke, E.S., 2000: 2. Boreal ecosystems in the global carbon cycle, *In* Fire, climate, and carbon cycling in the boreal forest. Ed. Kasischke, E.S. and Stocks, B.J. pp. 19-30, Springer-Verlag New York, Inc. U.S.A.

Kirscbaum, M.U.F., 1995: The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic storage, *Soil Bio. Biochem.*, **27**, 753-760.

Kolchugina, T.P. and T.S. Vinson, 1993: Equilibrium analysis of carbon pools and fluxes of forest biomass in the former Soviet Union, *Can. J. For. Res.*, **23**, 81-88.

Kurz, W.A. and M.J. Apps, 1995: Retrospective assessment of carbon flows in Canadian boreal forests, *In* Forest Ecosystems, Forest Management and the Global Carbon Cycle, Ed. M.J. Apps and D.T. Price, p. 173-182, NATO Advanced Science Institute Series, Berlin Heidelberg.

Lucarotti, C.J., 1980: The effect of fire and forest regeneration on mesofauna populations and microfungal species in lichen woodland soils, *McGill Sub-arctic Research Paper*, **32**, 7-26.

Matveev, P.M. and V.A. Usoltzev, 1996: Post-fire mortality and regeneration of Larix sibirica and Larix dahurica in conditions of long-term permafrost, *In* Fire in Ecosystems of Boreal Eurasia, Ed. J.G. Goldammer and V.V. Furyaev, p. 366-371, Kluwer Academic Publishers, the Netherlands.

Moore, T.R., 1980: The nutrient status of subarctic woodland soils, *Arctic and Alpine Res.*, **12**, 147-160.

Nadelhoffer, K.J., A.E. Giblin, G.R. Shaver and A.E. Linkins, 1992: Microbial processes and plant nutrient availability in arctic soils, *In* Arctic ecosystems in a changing climate. An ecophysiological perspective. eds. Chapin, F. Stuart (Francis Stuart), III *et al.* Academic press, Inc. San Diego, California. pp. 281-300.

Nakane, K., 1983: Estimation of root respiration rate in a mature forest ecosystem, *Jpn. J. Ecol.*, **33**, 397-408 (in Japanese with English abstract).

National Astronomical Observatory, 1998: Chronological Scientific Tables 1999, Edited by National Astronomical Observatory, Published by Maruzen Co., Ltd., 1998 Tokyo Japan.

Osozawa, S. and T. Kubota, 1987: A simple method to determine gas diffusion coefficient in soil, *Jpn. J. Soil Sci. and Plant Nutr.*, **58**, 528-535 (in Japanese).

Pietikäinen, J. and H. Fritze, 1995: Clear-cutting and prescribed burning in coniferous forest: Comparison of effects on soil fungal and total microbial biomass, respiration activity and nitrification, *Soil Biol. Biochem.*, **27**, 101-109.

Raich, J.W. and W.H. Schlesinger, 1992: The global Carbon dioxide flux in soil respiration and its relationship to vegetation and climate, *Tellus*, **44B**, 81-99.

Rolston, D.E., 1986: Gas Diffusivity, *In* Methods of Soil Analysis, Part 1. Physical and mineralogical methods, Agronomy Monograph no. 9 (2nd edition) p. 1089-1090, American Society of Agronomy, Inc., Soil Science Society of America, Inc., Publisher Madison, Wisconsin USA.

Rouse, W.R., 1976: Microclimatic changes accompanying burning in subarctic lichen woodland, *Arclic and Alpine Res.*, 8, 357-376.

Sawamoto, T., R. Hatano, T. Yajima, K. Takahashi and A.P. Isaev, 2000: Soil respiration in Siberian taiga ecosystems with different histories of forest fire, *Soil Sci. Plant.*, **46**, 31-42.

Schütz, H, W. Seiler and H. Rennenberg, 1990: Soil and land use related sources and sinks of methane (CH_4) in the context of the global methane budget, *In* Soils and the greenhouse effect, Ed. A.F. Bouwman, p. 269-285. John Wiley & Sons Ltd., Great Britain.

Shibuya, M., T. Sugiura, K. Takahashi, T. Sawamoto, R. Hatano, J.Y. Cha, K. Fukuyama, A.P. Isaev and T.C. Maximov, 1999: Allometries and aboveground biomass of a 22-year-old stand of *Larix cajanderi*, *In* Proceedings of the Seventh Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1998, Tsukuba, Japan.

Singer, M.J. and D.N. Munns, 1999: Soils: an introduction—Fourth edition, p. 163-226. Prentice-Hall, Inc. Simon & Schuster/A Viacom Company, Printed in the United States of America.

Soil Survey Staff, 1990: Keys to Soil Taxonomy, SMMS Tech. Monograph, 19, 4th ed.: 357-371.

Steudler, P.A., R.D. Jones, M.S. Castro, J.M. Melillo and D.L. Lewis, 1996: Microbial controls of methane oxidation in temperate forest and agricultural soils, *In* Microbiology of atmospheric trace gases. Ed. J.C. Murrell and D.P. Kelly, p. 69-81, Springer, Berlin.

Valendik, E.N., 1996: Temporal and spatial distribution of forest fires in Siberia, *In* Fire in Ecosystems of Boreal Eurasia, Ed. J.G. Goldammer and V.V. Furyaev, p. 129-138. Kluwer Academic Publishers, the Netherlands.

Yajima, T., K. Takahashi, E. Sasaoka, R. Hatano, T. Sawamoto, B.I. Ivanov, A.P. Isaev and T.C. Maximov, 1998: Stand structure and biomass of Larix cajanderi forest in the Siberian Taiga, *In* Proceedings of the Sixth Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1997, Ed. S. Mori, Y. Kanazawa, and G. Inoue, p. 72-80, March 1998, Tsukuba, Japan.

Zelenev, V.V., 1996: Assessment of the average annual methane flux from the soils of Russia, Working Paper—96-51 May 1996, IIASA (International Institute for Applied Systems Analysis, A-2361 Laxenburg Austria.